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FEASIBILITY STUDY OF ORBITING STANDARDS PLATFORM

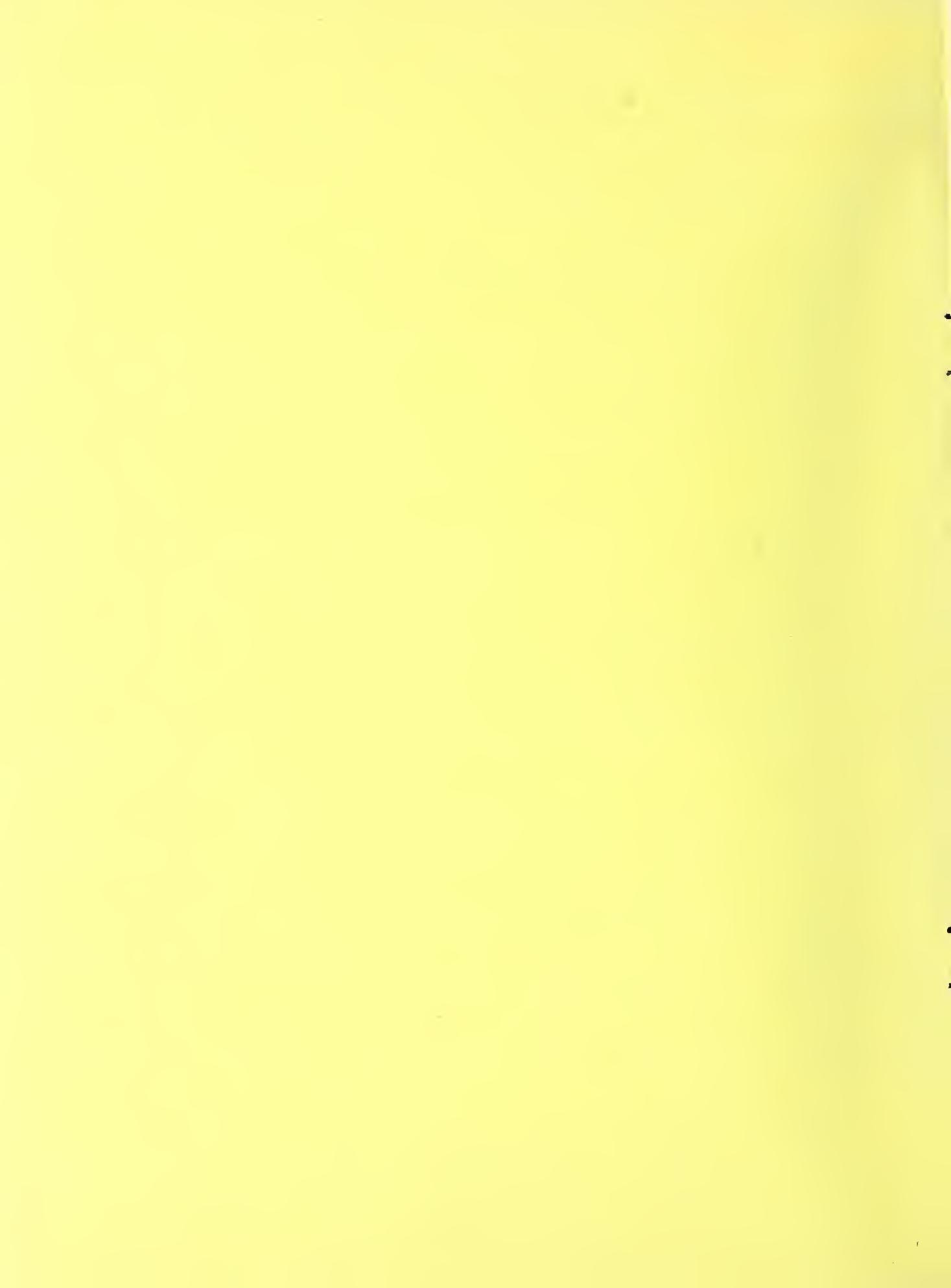
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National Bureau of Standards
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NBSIR 78-886

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NBS Interagency Report # 78-886

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FEASIBILITY STUDY OF ORBITING STANDARDS PLATFORM

A. J. Estin and R. C. Baird

This report consists of four components of a feasibility study for a satellite-based measurement system for determining important operational parameters of satellite communications systems and its major sub-systems. We have addressed the questions of required accuracy, methods of attaining and maintaining measurement accuracy and traceability, system tradeoffs, and economic impacts and benefits.

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FEASIBILITY STUDY OF ORBITING STANDARDS PLATFORM (OSP)

A. J. Estin
and
R. C. Baird

SUMMARY

Under the joint sponsorship of NASA Goddard Space Flight Center, Office of Telecommunications Institute for Telecommunications Sciences, COMSAT Laboratories, and National Bureau of Standards Electromagnetic Fields Division, a preliminary investigation has been undertaken into the technical and economic feasibility of using a satellite system to make accurate measurements on the many satellite communications systems and sub-systems in operation and being prepared for use. This report represents the contribution of the National Bureau of Standards to this investigation. It consists of four parts, as called for in the Statement of Work attached to NASA/GSFC PR No. 952-45635, dated February 1, 1977. These four parts are designated in the Statement of Work as "Deliverables": (5.2) Identification of accuracies of measurement required; (5.3) Definition of the method that will be used to verify Orbiting Standard Platform (OSP) measurements; (5.4) OSP tradeoff study; and (5.1) Benefits and cost analysis of an OSP. These parts appear in this report in the order listed.

Early in the course of this feasibility study, a survey was taken under the leadership of Dr. H. T. Dougherty of OT/ITS among potential users of the OSP system to ascertain the nature of their requirements and to serve as a basis for preliminary design of OSP. The results of this survey indicated overwhelmingly that, (a) there is a significant need for this kind of measurement capability, and (b) that there is support for this approach. In Part A of this report, we have summarized in some detail, and with as much quantitative specifics as were warranted, the types and accuracies of measurements to be made. These requirements are sufficiently within the capability of present day state-of-the-art measurement technology that they constitute a set of realistic goals for this project. Nevertheless, the technical challenge of performing such measurements rapidly, and automatically, in an unattended space environment, while insuring traceability to fundamental laboratory standards will itself be a significant advance in measurement science.

Part B of this report discusses the major aspects of this technical challenge, and outlines a proposed approach. Recent developments in microwave measurement techniques at the National Bureau of Standards, including principally the Six-Port, the Type IV power meter, and antenna near-field measurements and transformations, have provided an adequate basis on which this program can rest. Part C examines the various alternatives to OSP and within OSP that should be addressed before major aspects of the design are

frozen. Many of these considerations dovetail into the studies performed by Mr. Walter L. Morgan of COMSAT Laboratories, who has examined state-of-the-art space electronics and vehicle technology in order to assess such requirements as vehicle size, weight, and power requirements and consequent cost considerations. The last part of this report, Part D, discusses several important aspects of the economic impacts of the OSP system. It can be concluded that the system, which might cost in the neighborhood of several million dollars a year (including development, design, and deployment of a satellite, procurement of the necessary supporting earth station, and operation of the entire system) will return to the nation many times over this amount in terms of benefits to reduced capital and operating costs of satellite communication systems, resolution of procurement disputes between vendor and operator of these systems, supporting and aiding U.S. export of satellites and earth stations, and--most important of all--in extending the all too limited commodity of spectrum and orbit space available to us.

We wish to acknowledge with greatest pleasure the support and cooperation of our colleagues W. L. Morgan of COMSAT Laboratories, T. Keating Jr. and J. J. Woodruff of NASA Goddard Space Flight Center, and H. T. Dougherty of Office of Telecommunications Institute of Telecommunications Sciences. We are grateful to other persons (too numerous to list) from our respective organizations, as well as those from the community of satellite communications who have assisted and guided us.

Part A. USER ACCURACY REQUIREMENTS FOR SATELLITE COMMUNICATIONS SYSTEMS

The purposes of this part of the report are to define the various parameters which are useful to the deployment and operation of a satellite communications systems and, insofar as possible, to define the accuracies required. Such a tabulation is needed as a basis for later trade-off decisions as to exactly which quantities OSP should be designed to measure and in structuring the uncertainty limitations upon the measurement and re-calibration procedures. The importance of obtaining careful and exact uncertainty statements is that the overall resulting error budget goes far toward demonstrating a cost/benefit relationship for the entire project. More succinctly, the specific uncertainty required in a measurement places that measurement's difficulty somewhere between trivial and beyond the achievable state-of-the-art, and reflects accordingly in its cost.

In this report, we have attempted, on the basis of "The OSP Survey Response" [1] and other literature [2,3] to identify all possible parameters of interest and to deduce whatever user accuracy requirements have been set forth.

We do not in any sense imply that all of these parameters are to be evaluated by means of OSP, but only that these are quantities that are of interest to a satellite communications system operator, manufacturer, or regulator. The question of specifically which parameters OSP will measure will be addressed in a preliminary way in Part B on "Verification Methods," and more completely in the subsequent cost/benefit study.

We can generally divide parameters associated with these systems into three categories of system operation and testing: I. Signal radiation, transmission, and reception; II. Frequency and spectral characteristics of sources, signals, and receivers; and III. Mechanical properties of systems. These are listed at the end of Part A in Tables I, II, and III, respectively. While there is some room for discretion in such a classification (for example, is phase noise a signal-reception or a spectral parameter?), it is useful in making a first order cut on what OSP should not do and as a completeness and procedural check list on what it should do. These parameters may be useful and significant to either satellite or earth station (or both) and to either transmission or reception (or both). We have indicated this by checking appropriate columns in the tables.

The "accuracy" requirements given in the list are obtained, as is mentioned above, from a variety of user sources. Thus, they represent a broad range of reliability and thoughtfulness. The question of definition of accuracy/uncertainty of a measurement is quite complicated, when one attempts detailed quantification, and must be the subject of a very careful and complete analysis.

A further factor complicating this error analysis is the selection of how component errors are combined. Random independent errors are usually assumed normally distributed. Systematic errors, however, are not at all so straightforward, as they can have many different distributions (uniform, binary, Gaussian, etc.) and the method of propagation of errors may be difficult to establish. Moreover, it is not always even clear whether a given source of error is random or systematic and whether correlations exist between different errors in the budget. [4]

This discussion on errors and uncertainties does not directly apply to the results reported herein, but is included in order to place the longer term goals of the project in perspective. For the present, the "user accuracy" is stated in the tables under whatever form seems convenient, with explanatory remarks as appropriate. In view of the preliminary nature of this series of reports, a more definitive statement of accuracies seems neither warranted nor feasible.

TABLE I. SIGNAL RADIATION, TRANSMISSION, AND RECEPTION

Trans. Rec.	Satellite	Earth Station	Parameter	Accuracies & Remarks
			A. Antenna Characteristics	
			1. Pattern (Field Magnitude)	All quantities strongly frequency dependent.
X X	X X		a) On-axis gain	0.1 dB
X X	X X		b) Off-axis structure of main lobe	0.05 dB (Sat); 0.1 dB (E/S)
X X	X X		c) First and second sidelobes	0.5 dB (Sat); 0.2 dB (E/S)
X X	X X		d) Beamwidth; specific contours, e.g., 3, 4, 10, 20 dB	Measure of interference
X			e) Footprint; beam isolation of multiple antennas.	and coverage
X X	X		f) Gain/System temperature	Frequency reuse
X			g) Sidelobe envelope	Accuracy strongly depends on freq. & antenna gain. ITU Requirements
			2. Polarization (Axial ratio, tilt angle, ellipticity angle, etc.)	
X X	X X		a) On-axis properties	0.5 dB for axial ratio < 2dB
X X	X X		b) Off-axis structure of main lobe	Same
X X	X X		c) First and second sidelobe peaks	Same
X X	X X		d) Sidelobe crosspolarization	To 35 dB below main lobe co-polarization
X X	X X		e) Mainlobe crosspolarization	Below 30 dB down (Sat) " 32 dB down (E/S)
			B. Signal Characteristics	
X X			1. EIRP	
X X	X X		2. Field at antenna	Magnitude and polarization
X			a) Flux density to saturate transponder	0.5 dB
X X	X		b) Power input to antenna	0.2 dB
X			c) Backoff	0.3 dB
X X	X		3. Antenna power handling capacity	
X X	X		4. Gain stability	0.1 dB
X X	X		5. Gain/Operating temperature	See (A.1.f) above; for 4 GHz and G/T > 35 dB 0.2 dB for E/S; 0.5 dB (Sat.)
X X	X		6. Operating temperature and system temperature	20K (Sat) 1K (E/S)
X X	X		7. Carrier power/operating noise density	0.5 dB
X X	X		8. Propagation effects (atmos and ionsph)	
			a) Atmospheric attenuation	0.2 dB
			b) Cross polarization	0.2 dB
			c) Phase jitter	5°
			d) Group delay	0.1 nsec
			e) Group delay distribution	100 Hz BW
			f) Phase jitter and phase noise	5°
			g) Faraday rotation	

*NOTE: An "X" in one or more of the columns on the left means the parameter in question is relevant to that function.

X	Trans.	Satellite
X	Rec.	
X	Trans.	Earth
X	Rec.	
X	X	Station
	X	

TABLE II. SPECTRUM MEASUREMENTS

			<u>Parameter</u>	<u>Accuracies & Remarks</u>
A. Measures of Performance				
X	X		1. Frequency stability	
X	X		2. Modulation characteristics	
X	X		3. Spectral purity	
	X		4. Dynamic range	
X			5. Gain-transfer characteristic	0.1 dB (Sat)
X	X		6. In-band freq. response	
X	X		7. In-band group delay	
X	X		8. In-band group delay distortion	
X X			9. Turn-on transients	
X	X		-10. Error rate	
B. Measures of Interference				
X	X		1. Sideband rejection	
X	X		2. Spurious bandpasses	
X X	X X		3. Filter skirt shape	
X X	X X		4. Adjacent channel interference	
X	X		5. IM and other spurious signals	
X	X		6. Out-of-band emission	
X	X		7. Crosstalk	
X			8. Adjacent transponder interference	
X	X		9. Coding problems	

TABLE III. MECHANICAL MEASUREMENTS

			A. Position
X X	X X		1. Relative to earth
X X			2. Ranging
X X			3. Slew rate
X X			4. Tracking rate and accuracy
			B. Orientation
X X			1. Setting of attitude (roll, pitch, and yaw)
X X			2. Measurement of existing attitude (R, P, and Y)
X X	X X		3. Boresight
X X	X X		4. Pointing accuracy

Part B. VERIFICATION OF OSP MEASUREMENTS

I. The OSP System

In the previous part we have shown, in three tables, an essentially complete list of performance measurements useful in a Satellite Communications System. In this part, we shall select from that list those measurements which are suitable for measurement by OSP and we shall discuss the general means by which the validity of such measurements can be confirmed. In order to facilitate this selection, we shall first eliminate those measurements which clearly are inappropriate to OSP for at least one of the following four reasons:

1. Those parameters which the User* can efficiently and adequately determine for himself. (Examples: channel crosstalk, turn-on transients, error rates).
2. Those parameters which require radiation from OSP on frequencies that would interfere with assigned communications channels. (Examples: filter skirt shapes, bandpasses, and other broadband spectral properties of receivers.)
3. Those parameters which would require excessive space maneuvering on the part of OSP or offset of a User Earth Station antenna from its satellite thereby interrupting all service through that E/S. (Example: slew and tracking rates of an E/S.)
4. Those parameters which require maneuvering and precise roll, pitch, and yaw adjustment on the part of the user satellite. (Example: footprint measurement).

In general, the dividing line between those parameters which should and should not be measured by OSP finds practically all of the former in Table I and most of the latter in Tables II and III of Part A. It will be seen that almost all of those parameters most usefully measured by OSP can be determined from physical measurements (some absolute, some relative) of vector field strengths and power levels and phases of signals received and transmitted by the OSP system. We shall, therefore, proceed to outline the recommended measurement processes and discuss methods of verification for adequate support of these processes.

*The term "User" refers to the operator of the Satellite Communication System or other organization which is obtaining data from the OSP system.

The starting point for examining performance of a Satellite Communication System is the "Basic Link Equation," given below, which is easily derived from the well-known radar range equation for power transfer between two widely-spaced antennas:

$$\begin{aligned}
 \frac{C}{kT_{op}} \text{ (dB-Hz)} = & \text{EIRP} - 10 \log(4\pi R^2) + 10 \log \frac{G}{T_{syst}} - 10 \log k \\
 & + 10 \log \frac{T_{syst}}{T_{op}} + 20 \log \Gamma - 10 \log L_A
 \end{aligned} \quad (1)$$

where:

- C = Total received carrier power in the channel in question
- T_{syst} = Receiving system effective temperature under non-operating conditions. This includes antenna, receiver, background, sky, and atmospheric contributions, and is the temperature seen with a radio star measurement.
- T_{op} = Receiving system effective temperature under operating conditions. This includes T_{syst} plus the noise from the link transmitter and all noncorrelated interference.
- EIRP = Effective isotropic radiated power; the power radiated by the transmitter times the gain of its antenna in the direction of the receiver, expressed in dBw.
- G = Gain in the receiving antenna in the direction of the transmitter.
- R = Distance between antennas.
- Γ = Polarization coupling factor, $0 \leq \Gamma \leq 1$.
- L_A = Atmospheric losses.
- k = Boltzman's constant ($-10 \log k = 228.6$).
- All logarithms are to base 10.

The left side of (1), the ratio of carrier to noise density power, is a figure of merit for the link. Based upon fundamental information theory, this figure of merit sets an upper limit for the achievable data transmission rate, given an error rate. The carrier to noise density power ratio is normally measured at the User's Earth Station and is frequently measured on-line, without interrupting service. If all channels at the User's E/S show an acceptable value, the Satellite Communication System is operating satisfactorily, and no further action is normally required. On the other hand, if some channels show a degraded C/kT_{op} , the operator knows that system deficiencies are present, but in the absence of further testing cannot identify the causes. OSP would measure the various terms on the right side

of (1), and thus would be a reliable and accurate means of monitoring and diagnosing cause of system deterioration. Because OSP can act as an extremely well characterized sending and receiving terminal of a link between itself and the User's E/S, measurement of the relevant parameters of the E/S can be made directly (and also without interrupting service of the communications system). Although it might be feasible to also evaluate User satellite parameters in a direct way with OSP, several reasons indicate that this would be less efficient:

1. The determination of satellite parameters involves less measurement uncertainty if it can be made through a calibrated earth station rather than through a second satellite, even OSP. Ideally such an earth station should be as well calibrated as possible, which would mean, in descending order of quality of characterization: a) an NBS earth station designed for this purpose, b) another earth station to which NBS is able to obtain access and at least partially characterize, and c) the User's own earth station which would be characterized with the aid of OSP.
2. A link between OSP and a User Satellite would necessitate doubling the facilities carried on OSP. For example, OSP would normally carry receiving equipment for a Satellite Communications System uplink at 6 GHz and transmitting equipment for the downlink at 4 GHz. In order to work the User Satellite directly, it would be necessary to also include transmitting equipment at 6 GHz and receiving equipment at 4 GHz. Such an arrangement would nearly double the space and power requirements on OSP, would increase the control complexity significantly, and would greatly increase the probability of self-interference in OSP thus reducing its overall accuracy of measurement and its usefulness. In addition, spectrum allocation difficulties would become significantly increased.
3. The additional pointing requirements on OSP imposed by the need for reorientation to work a User Satellite would require severe orbit constraints as well as considerable fuel reserves for frequent large attitude changes. The near-synchronous orbit proposed for OSP, which is designed to meet earth-station calibration requirements, places OSP relatively close to its customer satellites, perhaps within 40 kilometers at point of closest approach. If we assume that the position box permits variation from assigned position of up to 0.1° in longitude or latitude, it is easily shown that satellite-to-OSP orientation errors could amount to over 60° if one of the two were precisely on station and the other were at the box limit in latitude. (See angle θ in Figure 1.)

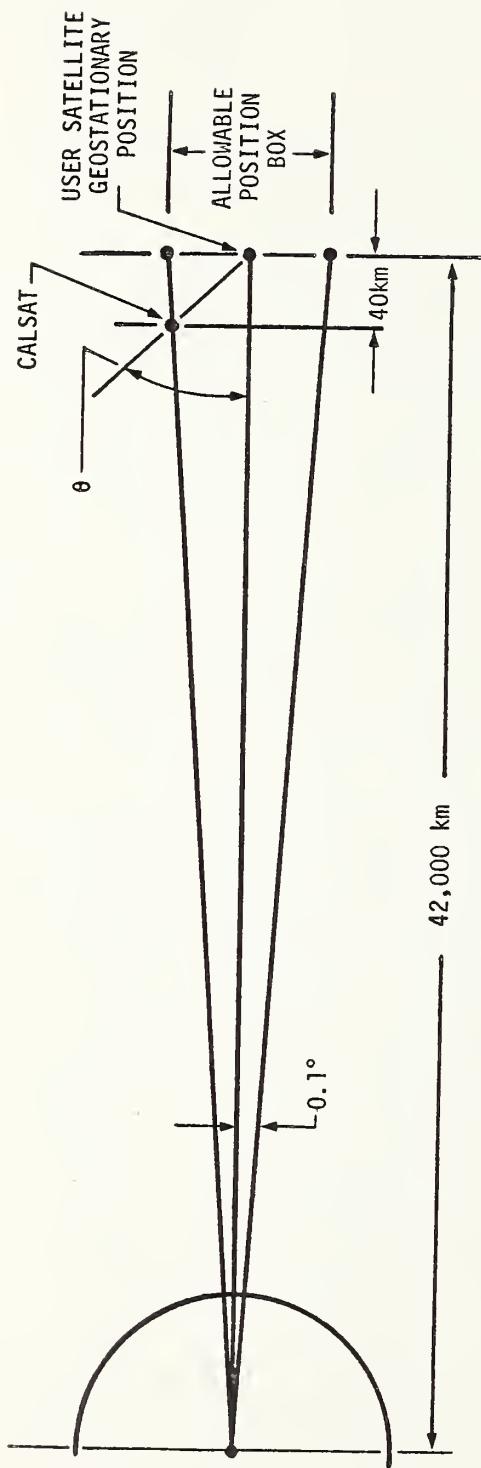


Figure 1. Satellite to OSP orientation error.

This would necessitate considerable roll, pitch, and yaw adjustment and control on the part of both the User satellite and OSP which in turn put unacceptable design constraints on both satellites. Moreover, a major attitude change on the part of the User satellite would be likely to interrupt his service.

Thus, we conclude that the initial OSP should be restricted to making transmit and receive mode measurements on the User E/S only, and not on his satellite. We will show subsequently how necessary measurements on the satellite can be made.

The method of verification of OSP measurements is basically two-fold. First, we will design into the OSP receivers and transmitters a variety of crosscheck and self-check procedures that are based on present NBS measurement developments and capability. Second, an earth station which has been independently evaluated and calibrated and which has excellent tracking and pointing capability as well as access to NBS measurement standards will be used to work OSP directly at predetermined intervals and can be used to confirm (or correct) operational characteristics of OSP after orbiting. This earth station must have its receive and transmit characteristics, especially on-axis gain and polarization, well enough measured that fields transmitted and received by it can be absolutely determined to high accuracy. The goal for on-axis determination is 0.1 dB. Polarization (circular and linear) must be pure enough and well enough established so that measurements made on OSP are not degraded by E/S uncertainties. An added dividend which will be considered later in more detail is that having such extremely well characterized satellite and earth terminals of a single link will enable resolution of propagation uncertainties such as atmospheric cross polarization, phase scintillation, and other anomalous effects in all frequency bands of interest. Figure 2 shows schematically the interactions of the components of the User Satellite Communications System and the OSP system.

II. Measurement System Configuration

A typical receiving/measuring/calibration/transmitting unit on OSP will be designed in modular form, where each module will be used at a certain number of discrete frequencies in one or perhaps two adjacent frequency bands. Such a "measurement module" will then be replicated in as many frequency bands as is desired to supply OSP service. Tradeoffs in the design of specific components of the measurement module will determine the number of specific frequencies and bands that can usefully be covered with a single module, and therefore how many are required. For example, mismatch magnitudes in the polarizing network of an antenna feed section ultimately

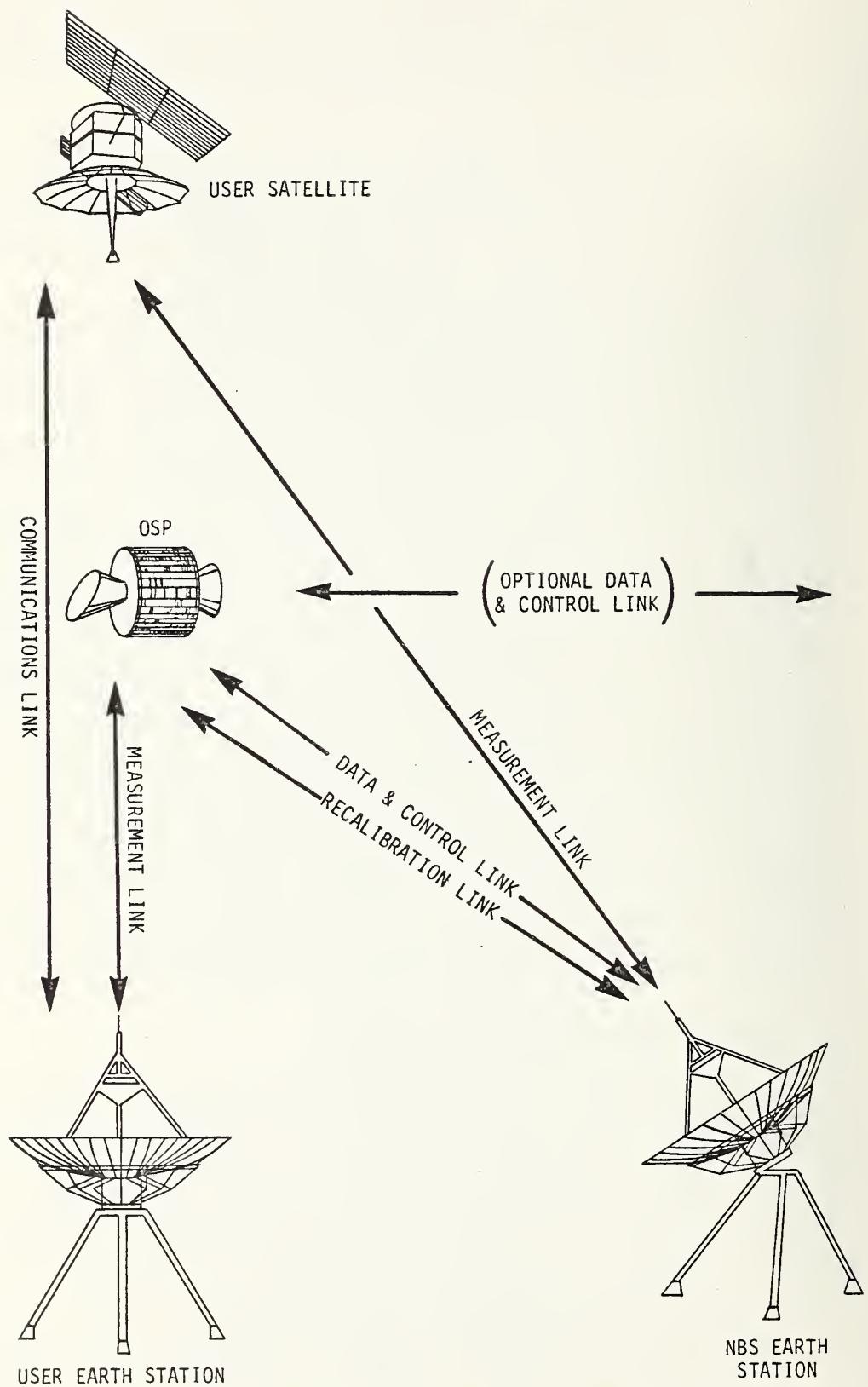
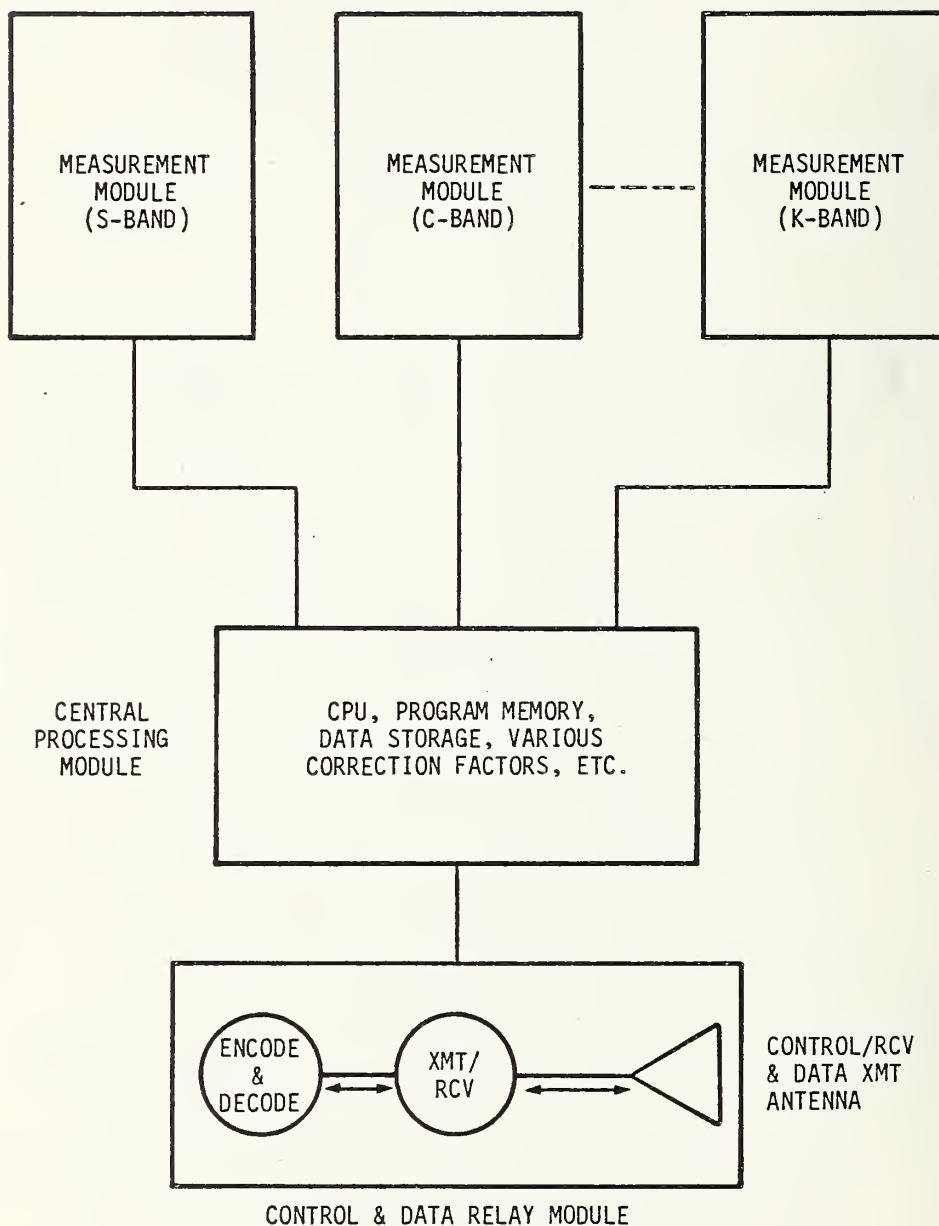


Figure 2. OSP system interactions with user system.

determine its useful band limits, within which a computer-stored calibration and correction procedure can be used to reduce the residual error to an acceptable amount at each desired spot frequency. Certain common elements, such as computer control and interfacing, will, of course, be external to the measurement module. These are designated as the "command, control, and data relay module," the "central processing module," etc. Their relationship to the measurement module is shown in Figure 3. Their functions, which are not critical to the subject of this report, will be addressed and discussed only as necessary to the understanding of the actual measurement process and its verification. We show in Figure 4 a block diagram of a typical measurement module. We might note that, although this diagram shows a duplexed (transmit and receive) signal antenna, the choice between having that arrangement and separate transmit and receive antennas is a matter for the equipment designer to decide, based on the design limitations of available components and weight/volume/space tradeoffs on the vehicle. The sections shown in boxes represent specialized measurement sub-systems and are discussed in some detail following:

- (A) Signal Antenna and Polarizing Network. The signal antenna is a stable horn having approximately 20 dB gain, which with the aid of the polarizing networks receives or transmits a pure circularly or linearly polarized wave, as called for by the central processing module. Circular polarization can be either right or left hand, and linear polarization can be at any desired angle. In this way, either desired or undesired polarization components can be sent or received. Gain, axial ratio, and tilt angle of the antenna will be predetermined for all required angles and directions off bore-sight and for each required frequency by means of accurate near-field techniques developed by NBS. These data and suitable interpolation routines can be stored in computer memory so that magnitude and configuration of any field received by this antenna from an E/S can be accurately determined within the error of non-calculatable atmospheric effects from measurements made by the Measurement Module. Similarly, the magnitude of any signal transmitted from OSP can be predicted at the aperture of the E/S being worked. Calibration factors on the polarization network will be measured and stored so as to be applied as corrections on measurements.
- (B) Six-port Networks for measuring transmitted and received power. The six-port network is a new method developed at NBS for measuring complex microwave power flow (phase and amplitude of incident and reflected waves) in a transmission line without significantly affecting that power flow. A brief explanation of the properties of the six-port is given in Appendix I. It has a number of advantages



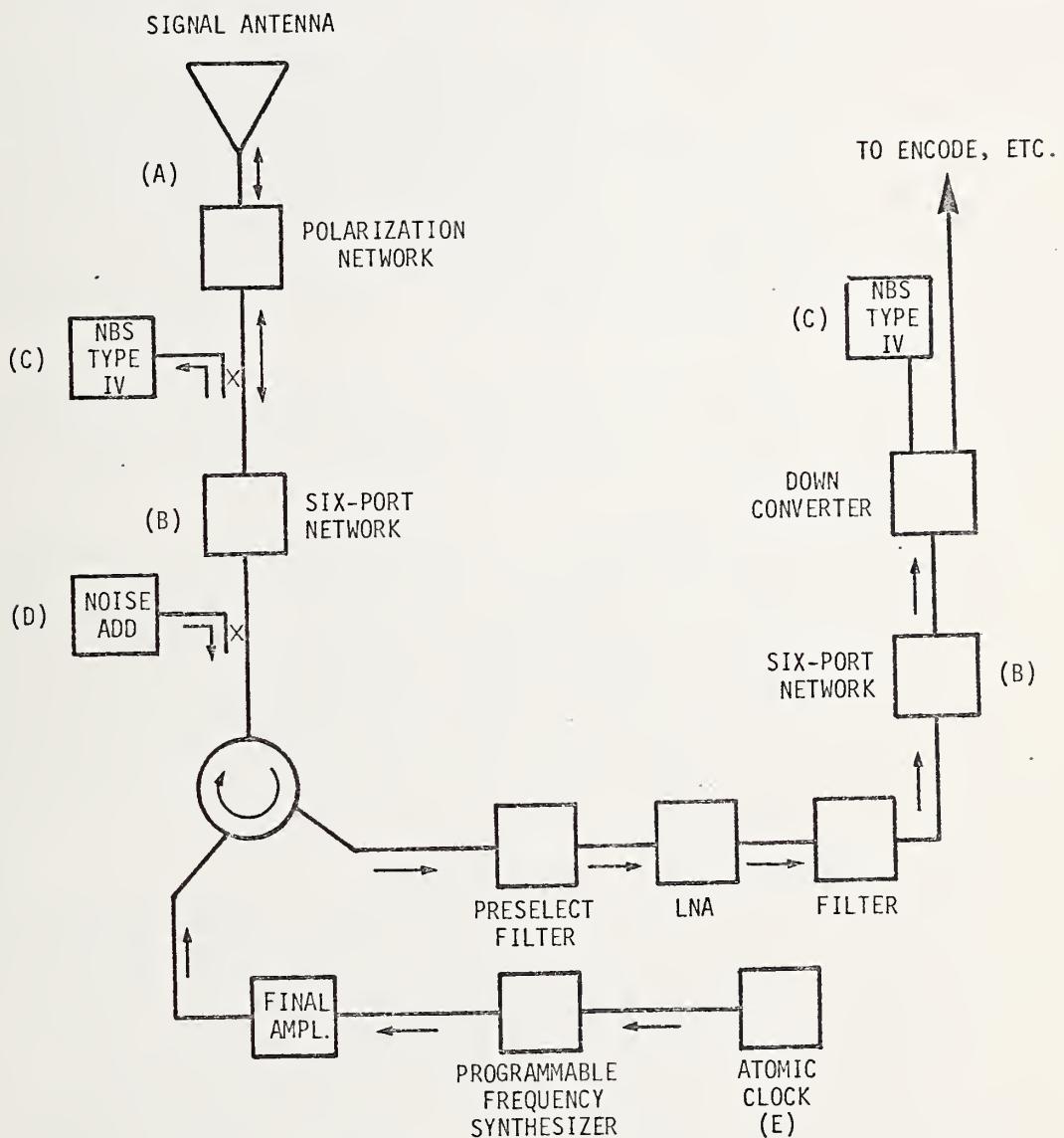


Figure 4. Measurement module.

that make it ideally suited for application in OSP:

1. It is accurate and has considerable redundancy in the measuring system. With the aid of computer control, self-test and self-calibration techniques can be included in the measurement. Partial system failure can be tolerated with little or no loss of information or accuracy because of the intrinsic redundancy.
2. It can measure over a dynamic range of 30 dB with accuracies of .05 dB or better, and over wider range at reduced accuracy.
3. Using sample-and-hold techniques, measurements can be made in one to ten milliseconds, at a rate of ten to one hundred measurements per second.
4. Frequency and temperature compensation are straightforward with computer control.

The six-port networks would be used in OSP both to measure received signal levels and to monitor transmitted signals and thus insure that no shift in level had occurred in the signal source or power amplifier of OSP.

(C) NBS Type IV Power Meter. This power meter is a self-balancing dc substitution device capable of making absolute microwave power measurements to an accuracy of better than 0.1%. It is intended to serve for periodic absolute calibration of both received and transmitted signals. Since normal measurement time required is of the order of several tenths of a second, it will not be used for routine measurements, but only with test signals for recalibration of the six-ports.

(D) Noise-Add Source. The noise-add is a solid-state diode which is triggered periodically in the course of a received power measurement. The known amount of noise power added to the measurement enables the effects of system gain changes to be removed, thus increasing accuracy ten to one hundred fold. It also is used for a front end temperature measurement and thus provides an additional cross-check on absolute received power level measurements.

(E) Atomic Clock. This is an optional component which might be used as a phase lock for the programmable frequency synthesizer so that phase jitter, group delay, and other measurements of propagation phenomena that require a common phase reference at both ends of the path can be made.

All other components of the receiving and transmitting systems are not intrinsic parts of the precision measurement process, but serve to select or reject, amplify, convert, encode and decode, and otherwise process measurement, control, and data signals.

III. Earth Station Checking and Recalibration.

The National Bureau of Standards is proposing a program initiative to the Department of Commerce for establishing an Earth Station at its Boulder, Colorado, site which will provide a means for recalibrating OSP. The NBS E/S will consist of a parabolic dish (approximately 10 meters) of extremely precise surface with advanced tracking and pointing capability. It is anticipated that receive and transmit capability from 2 to 30 GHz will eventually be acquired. Direct communications with OSP may be maintained (as one of several possible means) of exercising command, control, and data acquisition functions. The dish will be thoroughly evaluated by means of spherical and cylindrical near-field scanning techniques developed by NBS. These measurements will provide a complete farfield pattern at each required frequency, including gain and polarization structure for off-boresight conditions, as well as radiation characteristics deep into the sidelobe structure. With such a unique and meticulous evaluation, this Earth Station will be capable of measuring fields and noise at its aperture and generating test fields at OSP with an accuracy and precision never before accomplished. With this Earth Station, test signals to and from OSP can be periodically measured and thus confirm and update the accuracy being maintained by OSP.

In the same way that OSP transmits standard signals to User earth stations and performs measurements on signals transmitted from his earth stations, the NBS Earth Station will be used to work the User satellites directly.

Additional benefits can be derived from this combination of a well-characterized Earth Station and OSP. It is anticipated that one of the problems of extending satellite communications links to higher frequency bands, such as 20 and 30 GHz, is that atmospheric effects will become more pronounced and probably will in fact be the limitation to our ability to predict the performance of these links. Such phenomena as rain and snow depolarization, water vapor dispersion, atmospheric scintillation, and possibly ionospheric Faraday rotation need to be examined. Cross-correlation of these effects and measures of their correlation across the entire frequency spectrum will be needed in the future when millimeter waves become more fully utilized for communication links.

Part C. OSP TRADEOFFS

Many decisions and compromises must be made in the complete design and development of a system like OSP which involves new engineering concepts. This system is intended for calibrating and measuring performance parameters on satellite communications systems and subsystems, and the tradeoffs include: (1) Choices among possible methods of conducting these measurements, of which OSP is one possibility; (2) Prioritization of requirements and schedules among various classes of potential users; (3) Orbit considerations; (4) Nature of services to be offered; (5) Frequency and band coverages; (6) Hardware design; (7) Payload allocations to equipment, fuel, etc., and (8) Methods of processing data and disseminating results.

The purpose of this part of the report is to identify as many trade-offs as possible and to indicate the factors involved in resolving the necessary decisions. In a few cases, when the resolution of the trade-offs is already apparent we have so indicated and merely listed the considerations to complete the record. In most cases, however, the decisions are engineering, require quantitative design data, and must await a more advanced state of development of the project. In these cases, we indicate the preliminary nature of the decision required.

I. Tradeoffs among Various Methods of Measuring System Performance

(A) Radio Stars. Several possible alternatives exist in present and anticipated methods of evaluating gain, temperature, and other related parameters of earth stations. One of the main methods now in use utilizes the radio flux of one of several radio stars, Cassiopeia A, Taurus A, Cygnus A, and possibly our own sun and moon to measure G/T of an earth-station [5]. The advantages of using radio stars to determine G/T are:

1. The sources are of generally world-wide availability. Standards need not be carried to remote ground stations and used under conditions which degrade their accuracy.
2. Only moderate technical ability on the part of the user is required. "Cookbook" techniques are available and a massive measurement capability of hardware and supporting software is not required.
3. These stars are so-called "natural" standards which once evaluated need not be recalibrated, although steady changes in flux density will need to be monitored. The analogy is that of determining a very accurate length measurement based upon the appropriate spectral emission of Krypton 86 in contrast to obtaining it by comparison with the standard meter maintained in Paris, France.

4. The possibility exists of obtaining polarization data from the flux of stars.

The disadvantages are:

1. The "signal" level is low, and not suitable for sidelobe evaluation. If G/T of the earth station is too low, measurement accuracy becomes badly degraded. On the other hand, if the gain of the antenna is too high, the narrow beamwidth will resolve the fine structure of the star and thus also reduce accuracy.
2. The Starflux intensity is frequency-sensitive and, for most earth stations, becomes unusable above about 10 GHz. While it is true that discrete extraterrestrial sources, such as water molecules and various free radicals have been identified, their usability for this purpose remains to be determined.
3. A good pointing capability is required of the ground station. The ability to intercept a star is somewhat more demanding than locking onto a geostationary satellite.
4. The method requires total service interruption for periods of hours, and is usable only to obtain receive characteristics of the antenna.

(B) Comparison With Standard Gain Antennas. A second method of obtaining ground station antenna parameters is by direct comparison with a calibrated reference antenna. The advantages of this method are:

1. Accurate on-axis gain can be obtained. If the reference antenna has good polarization characteristics (very low axial ratio if used with circular polarization and very high axial ratio if used with linear polarization), then the copolarization of the antenna under test can also be obtained.
2. The method is economical and does not require high expertise on the part of the user.
3. It is available on a noninterrupt basis for on-axis measurements.

The limitations are:

1. It requires a steady and stable satellite beacon transmitter on the desired frequency.
2. Sidelobe data requires service interruption.
3. The measurement is available in the receive mode only and is subject to significant interference which cannot be corrected for.
4. Linear cross polarization is not available unless the antenna under test has a mount of unusual flexibility.

5. The attainable measurement accuracy degrades significantly if the reference antenna has significantly lower gain than the antenna under test. Typically, if the former has a gain of 30 dB and the latter over 50 dB, the three-sigma error can be almost 1.2 dB, whereas if the gain of both were 50 dB, it would be less than 0.1 dB for normal signal levels [6]. Attaining this low error, however, is not feasible, for it would mean having a calibrated reference antenna which is as large as the earth station itself.

(C) Near-Field Scanning. The National Bureau of Standards has been developing techniques of determining complete antenna properties by making thorough scans of the near field over a surface very close to the aperture plane. The characteristics of the antenna, including amplitude and polarization of the entire pattern, can then be calculated for any other distance from the antenna, including the usually-desired far field. The advantages of this technique are:

1. It gives complete information about the antenna, including mainlobe, sidelobe, and null structure down to the order of 60 dB below the boresight gain.
2. Data can be obtained at any frequency desired, transmit or receive, without fear of interfering or being interfered with.
3. The accuracy on a relative basis is the highest available by any known technique. Tying the on-axis gain to an absolute reference then enables one to achieve high accuracy on an absolute basis for the entire pattern.

The limitations are that expensive and sophisticated instrumentation, including hardware, computation facility, and software, must be used. It requires state-of-the-art measurement expertise. Extensive service interruption is needed, because of the large amount of data that must be taken and processed. As an example, if an antenna having a diameter to wavelength ratio of 500 were being measured (an 85-foot dish at 6 GHz), 2.5 million data points would be needed with a typical total measurement time of 20 hours. In addition, data processing in a CDC 6600 class computer would take about 30 hours.

(D) Calibrated Satellite and Earth Station. The OSP system with its supporting calibrated earth station answers most of the problems raised by examining the alternative approaches to measuring the receive and transmit properties of communications system satellites.

This system can measure all of the required parameters accurately and economically without requiring extensive skills of the User, without major interruption of his operation, and without converting every satellite and ground station into a standards laboratory. The investment in the OSP measuring system, its support, recalibration, and operation, of course, is major, but the purpose of this entire feasibility study is to evaluate the benefits derived against the costs.

II. Orbit Tradeoffs

Several types of orbits are under consideration for an operational OSP, most of which are near-geosynchronous. Although a low, or spacelab, type of orbit is important and can be useful for test and demonstration of the OSP concept and for obtaining vital design and operational data, it does not seem feasible for a fully operational system designed to interact with various user satellite communications systems. Two major reasons why this is so are:

1. Position control in a greatly sub-synchronous orbit would be exceedingly critical and might require almost continuous fuel expenditure to maintain precise passage relative to each individual user's geo-stationary satellite.
2. Even with satisfactory maintenance of passing position, a low orbit OSP would pass through a typical earth station half-power beamwidth in less than 10 seconds. This is far too rapid to conduct an extensive set of measurements with an acceptable degree of accuracy and definition on any antenna except one which has extraordinary tracking, positioning, and offsetting capability. Furthermore, it is clear that making such a series of measurements on an operating link would necessitate complete interruption.

Accordingly, since most of the functions of OSP would require a near-synchronous orbit, we list only the tradeoffs for various near-synchronous orbits.

- (A) Constant Drift. This is a circular equatorial orbit whose radius is slightly sub- or super-synchronous. It is fuel-conservative, but in order to transverse slowly enough to be useful, will require long unproductive periods during transit between satellites being serviced. Some fuel would be required to reverse the direction of drift at the ends of the sector occupied by users. The monotonic direction of drift (between reversals) would preclude opportunities to repeat measurements should the need arise.
- (B) Visitation Approach. This is a modification of the constant drift orbit, in which thrusters are used to increase the drift rate during the unproductive periods and then decrease the drift rate

for the measurement series. It is essentially similar to (A) in other respects, except that the fuel requirements would be increased significantly.

(C) Gravitational Well. This orbit is near geostationary, and makes use of the slight geopotential well which exists over the western hemisphere. The net effect is a self-reversal of drift over the Atlantic and the Pacific potential barriers. This is probably not feasible, because the drift rate (required to use these low potential barriers effectively) is so slow that an unacceptably long time would elapse between productive periods.

(D) Tilted Near-Synchronous Orbit. Tilting the constant drift orbit with respect to the equatorial plane would have the effect of making OSP oscillate in a north-south direction relative to geostationary satellites as it drifted. This orbit configuration would assist OSP to intercept links in which the user satellites were slightly out of the zero latitude position. Disadvantages are that unless the drift rate were exceedingly slow, such a path probably decreases, rather than increases, probability of boresight interception of a user link. Also, this path tends to be unstable, with the N-S oscillation tending to increase with time.

(E) Elliptical Orbit. With a near-synchronous elliptical orbit, OSP would appear to have an oscillatory drift across the orbital arc which would be superimposed upon easterly or westerly drift, depending upon whether the period was sub- or super-synchronous. The amplitude of the oscillatory motion is determined by the ellipticity of the orbit and the rate of drift by the departure of mean elevation from synchronous level. Although this orbit conceivably could be combined with equatorial tilt, the same objections as stated in (D) would hold. The problem of nonalignment with user satellites is probably not serious, and is likely to diminish still further in the future, as station-keeping box size is tending to decrease to and perhaps below 0.1 degrees [2]. One major advantage of the elliptical orbit is that multiple measurements can be taken on a given system without waiting for the return of OSP many months later. It would facilitate sidelobe measurements in the equatorial direction, which is the direction that is significant with respect to sidelobe interference with nearby satellites. One disadvantage is that fuel estimates and difficulties of the orbital mechanics have not been investigated as yet for this orbit. Another disadvantage is that of having a continually varying distance between OSP and the user earth station. This will, of course, affect the signal strength received at both places. The complexity introduced, however,

should be readily handled through software in the onboard computer and, if needed, by continuous control of the signal output level.

III. Users To Be Serviced

It became clear at an early stage of this study that the only Users who can be reasonably served are those with satellites in near geo-stationary orbits and those who are able to aim their earth-station antennas into this orbit. Fuel consumption required to take OSP in its equatorial near-synchronous orbit to and from other orbits would be enormous. It is also clear that the preponderance of satellite communication system operations would be served, even with this restriction. A second point that seems clear is that OSP will not perform measurements directly upon other satellites. Requirements of pointing control upon both OSP and the User satellite would be major--at least 60 degree changes in pitch and yaw and quite possibly 360 degree changes would be required. In addition to requiring major commitments to attitude controlling and determining capability on each satellite, fuel expenditures would increase markedly. Such drastic attitude changes on the part of the User satellite would take it out of service while being measured, an unacceptable consequence. Finally, transmit and receive capabilities on OSP would have to be doubled. It should be noted, however, that this does not mean the satellite end of the User link will not be served; only that it will not be served by OSP, but by OSP's companion earth station.

Within hardware restrictions, military and civilian users alike can be served, save only that the OSP system must remain completely free of security classification. Imposing secrecy of operating frequencies, methods of measurement, processing procedures, etc., would unacceptably limit the general usefulness of OSP, although NBS policy is that the results of a reimbursed calibration are the sole property of the purchaser of that calibration.

A design goal is to permit the User to maintain service of this system during the measurement, dedicating the equivalent of only one or a few audio channels to the measurement process.

An alternative which can be considered is to schedule measurements during periods when communication loads are light, as for example, past midnight. This, however, constitutes fine-tuning of the system and its feasibility must await resolution of many of the operational decisions.

IV. Hardware Tradeoffs

A great many engineering and operational tradeoffs must be resolved as the engineering design of the system proceeds. To some degree, these can be stated here, but since most of these involve quantitative evaluation of weight, power, volume, complexity, redundancy, interference, accuracy, economy,

realizability, and many other qualities, we cannot expect at this early state of the project to resolve or even fully identify them. Mr. W. L. Morgan has in his reports shown the scope of interdependence of these decisions and has begun a serious analysis. We shall not repeat his work here, but only suggest a few of the items that must be on a final checklist.

- (A) Frequencies and Band Coverage. The general lower and upper operational limits of OSP are approximately 2 and 30 GHz, respectively. OSP antenna size, NBS Earth Station size and surface precision, anticipated User system deployment, space available on OSP, and response to the User questionnaire [1], all combine to dictate these outer limits. The number of transmit and receive frequencies in each band, the number of bands, the spectral location of these, the amount of duplexing and diplexing, all are questions to be resolved. Some of the tradeoffs involved include obtaining design-center performance as opposed to accepting poorer hardware performance and compensating by means of software corrections.
- (B) Antennas and Polarization Networks. One of the most important components in the measuring system is the antenna and its polarization network. The earth coverage pattern and the polarization over that pattern must not only be well calibrated, but must maintain high purity. In addition, the internal circuit parameters must be such that mismatches are low and loss is minimized. Design of the antennas (probably microwave horns having gains of about 20 dB) and temperature stability must be carefully optimized, and this requirement must be balanced against the system economy of diplexing and duplexing.
- (C) Other Factors. Some of the questions that are especially important to a "satellite standards laboratory" as contrasted with a "satellite communications terminal" are very briefly suggested here. The tradeoff between cost and state-of-the-art feasibility on the one hand and desirable accuracy on the other hand represents the focal point of success of the project. As has been mentioned earlier, a tradeoff is available between quality hardware design and software improvement of performance. It is just this factor which has been a current subject of interest in many government and industrial standards laboratories and quality control facilities. The entire software problem of instrument control, data acquisition, data processing, customer queuing, and many other aspects must be engineered and allocated to on-board or ground computer facilities.

Part D. ECONOMIC IMPACTS OF PRECISION MEASUREMENT CAPABILITY
UPON SATELLITE COMMUNICATION SYSTEMS

I. Introduction

This part identifies economic and social benefits resulting from accurate measurement of satellite communication systems. As a general axiom, areas of science and technology benefiting most from an accurate, precise measurement technology are those already at an advanced, demanding state of technology. At early or rudimentary states of development, major technological concerns are primarily qualitative: that something exists is frequently adequate; that its quantitative nature be known is not necessary.

Satellite communication is an advanced technology in which there is little room for imprecise adjustments because of engineering and economic constraints imposed upon its systems. In an analogous sense, the performance of an advanced racing car is much more critically dependent upon precise tuning than that of an old, neglected jalopy. A small maladjustment in the former will cause a much more noticeable degradation in performance than in the latter. This part of the report describes various specific ways in which exact measurement capability acts to the benefit of planners, designers, operators, and suppliers of communication systems.

For the planner and regulator, an important concern is that of interference as determined by undesired interactions of systems with each other. From the operator's standpoint, efficiency of utilization depends upon obtaining adequate management data on performance and capital costs. Between the supplier and operator, questions may arise as to whether or not a major system component meets its specified performance, and therefore whether or not it is fulfilling incentive and delivery requirements. Measurement techniques which are accurate, credible (traceable), convenient, relatively inexpensive, rapid, and operationally noninterfering become valuable resources for all of these parties. It is our aim in this report to develop the basis for quantitative estimates of those values.

II. Impact Upon System Investment and Operating Costs

The Orbiting Standards Platform (OSP) and its supporting NBS Earth Station (NBSES) will be designed to make accurate measurements on several parameters, (listed in Table I) that are relevant to the performance of both earth stations and satellites. We will first discuss only those parameters concerned with improving the operation of the user's own system. These primarily concern measurements for evaluating signal and noise levels, especially gain and system temperature determinations of earth stations. We can arrive at an estimate of the worth of these measurements by assuming that uncertainty in the measurement must be compensated by an equivalent over-design of the system.

If a certain communication system has a target data rate and associated probability of error requiring a corresponding G/T of an earth station, then the uncertainties in achieving gain and temperature dictate a design goal G/T which must exceed the required operating values by at least these uncertainties. The cost of this over-design can be approximately quantified by evaluating the incremental costs of each individual parameter per unit of measurement uncertainty. A complete analysis would require that all relevant parameters be considered, that all alternative methods of measurement and their uncertainties be analyzed, and that these data be summed over all the existing and planned systems. Recognizing the impracticality of such a complete analysis under the constraints of available time and resources, we must select the most significant elements and only indicate the magnitude of the total effect.

One of the most important link parameters to be considered is the G/T of an earth station, that is, its figure of merit. We will examine separately consequences of gain and system temperature measurements of electrically and physically large antennas.

Three studies performed in the late 1960's attempted to make empirical analyses of the costs of large earth station antennas [7,8,9]. Each study obtained cost formulas which have been re-examined and enlarged upon recently [10] and updated to 1974 [11]. Although it is necessary to account for inflation, advances in manufacturing technology, and increased competition, in order to extrapolate these costs to the present and future, the consensus is that the effects of these perturbing factors on incremental cost dependence upon size are probably second order. Accordingly, with the aid of figure 5, one can obtain a reasonably consistent picture of incremental costs. There is generally good agreement among these estimates of cost, especially for costs of antennas above approximately 50 feet in diameter. A straight-line (log-log) composite of these curves, from which none of the individual curves departs by more than 10%, indicates a cost in hundreds of thousands of dollars equal to one-fourth of the square of the antenna diameter (in feet). To a good approximation, a gain-change of 1 dB corresponds to an increase in diameter of 11.5%. One can therefore conclude that the cost of antennas over 50 feet in diameter rises about 23% per dB. This corresponds to a cost-effectiveness of measurement in which reduction of uncertainty is worth between \$150,000 and \$2,500,000 per dB, for 50- and 150-foot antennas respectively. (These are probably the lower and upper limits of validity of this model.) One must bear in mind, of course, that an antenna is not actually purchased because it has a gain of so many dB, but rather because it is in a certain size class. As a statistical averaging, however, this approach to costing seems reasonable and valid.

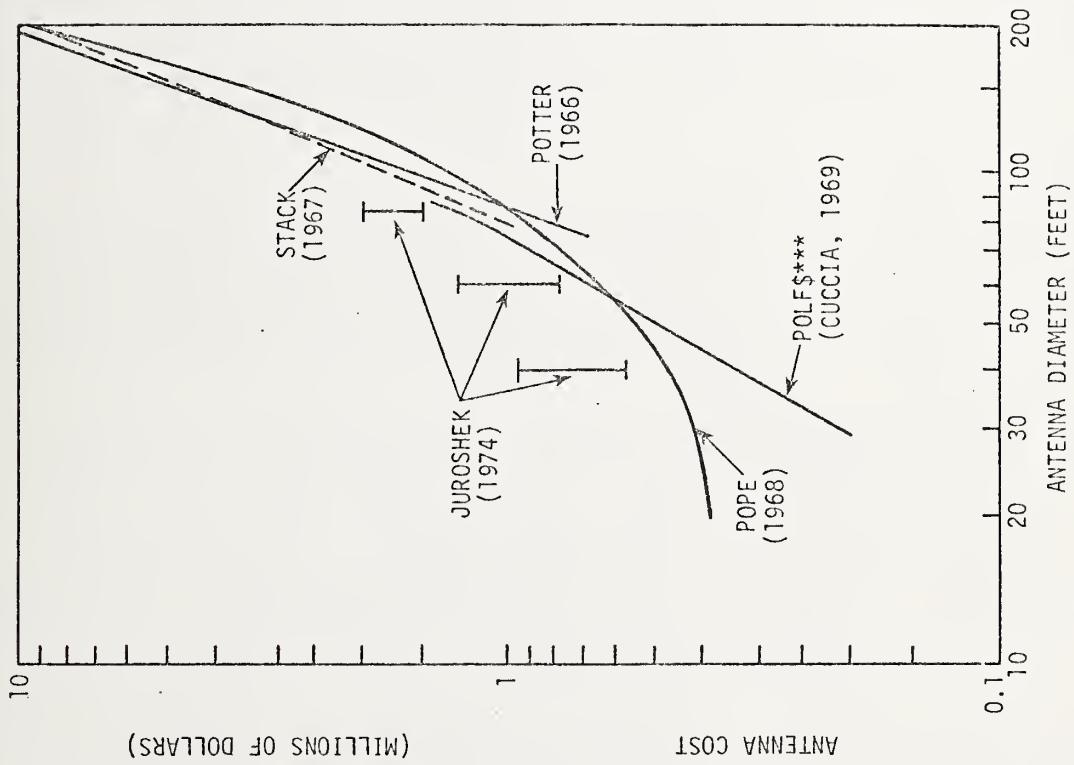


Figure 5. Costs of large aperture parabolic antennas.

Present typical accuracies of measurement of antenna gain are about 1 dB, but errors of several dB are not uncommon [5]. The estimated uncertainty to be achieved by OSP and its support NBSES will be in the vicinity of 0.1 to 0.2 dB. The increased accuracy, using this measurement alone, may well reduce the cost of purchasing hundreds of earth stations by the amounts stated above, for a cost savings on the order of \$100 million.

The system temperature is the other factor that affects G/T measurements. The principal contributors to system temperature are antenna factors (efficiency, sidelobes, and feed losses) over which relatively little control is available; and noise temperature of the low-noise receiving front end, (LNR), which can be reduced by purchasing more expensive front-end electronics. In general, for large antennas the LNR costs are small compared with other capital costs but are still important to performance. As the antenna diameter is reduced, the cost of lowering the noise temperature of the LNR becomes an increasingly large part of the station's cost [10]. The difficulty of measurement increases and the LNR costs rise abruptly as the noise temperature decreases and as the frequency increases above 10 GHz. Finally, we note that the use of radio stars for measurement of G/T becomes increasingly inaccurate and difficult for these cases of small terminals and higher frequencies [12].

Putting these factors together in a qualitative way, we conclude that a typical noise measurement would be made on an 8 GHz system with an LNR temperature of 30 K. For a typical total front-end temperature of 70 K (antenna plus LNR), the measurement uncertainty would be about 10 K, which amounts to a fractional error of 30% on the LNR, which is the only controllable part.

The steeply rising costs of cooled paramps with lower noise figures are shown in figure 6, which is reprinted from reference [13]. Very recent data [14] on cooled paramps agree with that of figure 6. This figure covers a sufficiently wide range so we may conclude that the cost in the range of noise temperature from 10 to 100 K is inversely proportional to the temperature, or that the fractional cost increment is equal to the fractional uncertainty of the temperature measurement. Combining this result with that of the previous paragraph, we can see that the worth of a factor-of-five improved temperature measurement is \$7000 per receiver, with the number of LNR's in use measured in the hundreds. Thus, although OSP can decrease the cost of over-design on both temperature and gain of earth stations, the dominant benefit is through the gain component of the G/T ratio.

Accurate measurement capability can also favorably affect satellite communication system investment (capital) costs when replacing major equipment, especially satellites. The principal system operators, such as INTELSAT, have replacement satellites in orbit in anticipation of the failure of

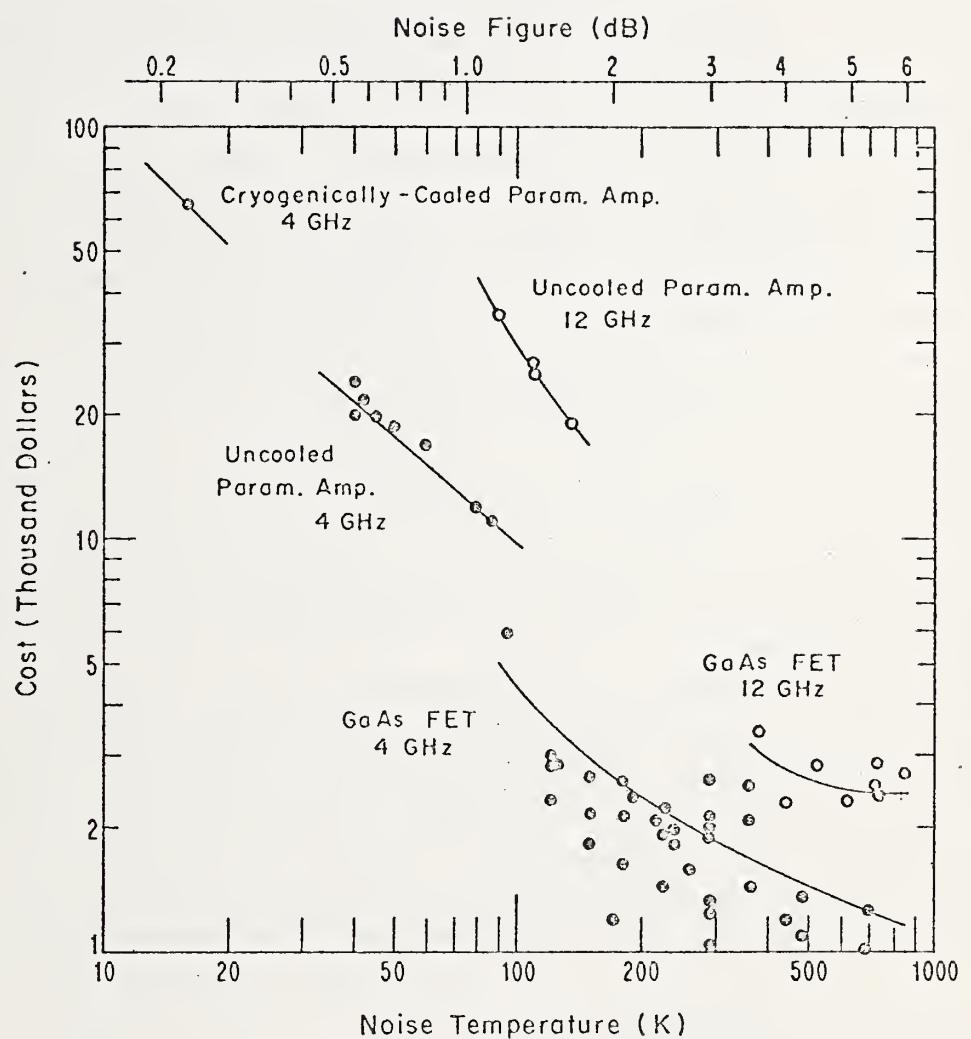


Figure 6. Costs of low noise front ends (Courtesy Akima [13]).

operating satellites. Such failures occur for one of three reasons: (1) exhaustion of fuel used for precise station-keeping; (2) sudden death of a sufficient number of on-board transponders so that the satellite cannot maintain adequate data rates; and (3) slow degradation in the satellite EIRP so that error rates increase to unacceptable levels because of poor signal-to-noise ratios. All of these factors are presently estimated on the basis of statistical predictions, and satellite replacement schedules are generated accordingly. Especially with respect to the last failure category, the ability to make measurements with negligible interruption of service provides a method of continuous quantitative determination of the state of health of the various transponders in the satellite. Such a record of performance vs. time (which is analogous to the Control Charts in common use in standards laboratories) enables the system operator to maintain continuing surveillance on the performance of the system and thereby to accurately schedule the launching of replacement satellites and upgrading of earth station equipment. The advantage of such system management information is that capital and replacement costs are reduced in several ways: (a) satellites are launched at a more accurately defined time of need and thus their costs are postponed until actually needed; (b) too early launch requires that the satellite be idle for a longer period prior to use. During this time, degradation, failure, and use of fuel all continue to exact their toll; (c) delaying the launch permits taking advantage of late advances in state-of-the-art in equipment needed.

Assuming a launch plus equipment cost of approximately \$10 million per satellite, the ability to delay deployment of these replacement units for an additional year every seven years means a savings of more than \$1 million per satellite. In the same way, the general condition of the system can be more closely monitored so that maintenance and repairs can be anticipated before major indicators arise, such as: breakdown, complaints from subscribers about quality of service, and actual loss of operating channels.

III. Payment of Incentives

Usually, procurement of major satellite communication components is contingent upon the vendor's fulfilling a set of incentives. Payment for these incentives, significant increments to the basic purchase price, frequently make the difference between the vendor's profit and loss on a satellite. As an example, the satellites comprising the Global Positioning System (GPS) will carry a total of approximately \$20 million in incentives.

The conditions upon which incentives are based are usually stated in terms of satisfactory operation of a specified number of channels over a certain period of time. Complete breakdown on the one hand and completely satisfactory service on the other are conditions which raise no controversy

between purchaser and vendor. Marginal performance, however, can lead to considerable difficulty and expense in resolving whether the incentives have been met. It is possible that apparently defective performance of a satellite (such as low EIRP) is actually indicative of a faulty measurement from an earth station. The combined role of OSP and NBSES can be that of a neutral third party in resolving such difficulties [12].

IV. Effective Utilization of Spectrum and Orbit Resources

In the previous sections, we have emphasized those measurements considered most important by a system operator because parameters of signal and noise directly affect the performance of his own system. With the present and future trend of dense packing of systems into the frequency spectrum and the geostationary orbit, the problem of interference between separate systems becomes an important matter of regulatory, and therefore of public, interest. Even with current trends toward frequency re-use by means of orthogonal polarization, spot coverage, and extension to the higher frequency bands, it is clear that available frequency channels and orbital positions are being filled rapidly.

The satellite communication industry has an exploding market. Today, some sixty systems either are in operation or are being planned. The economic and societal consequences of this kind of growth are both far reaching and difficult to predict adequately. Joseph N. Pelton, of INTELSAT, recently wrote [15], "When people seek to predict the future, they frequently are guilty of two errors. They underestimate how quickly a new technology can take off, and they overestimate the ability of institutions and policy makers to cope with the resulting societal impact." By way of analogy, he points out that in 1950, "fearless forecasters" suggested that there was no real market for computers, since twelve computers, with the speeds then possible, could perform all necessary calculations for the United States, and two could satisfy the needs of the United Kingdom. W. L. Pritchard [16] seconded Pelton's viewpoint, saying that we tend to be terribly conservative in our long-range predictions. He adds, "It is even conservative to predict that by the end of the century (based upon population growth, increase of per capita GNP, and concomitant increase in demand for communications services) there will be three times the present number of satellites in orbit."

In the future, there will be a tremendously increased load upon available resources of frequency spectrum and geostationary locations. Attempts to stretch these limited resources are taking a number of forms, including refined coding, use of time-division-multiple-access, multiple-beam satellites, orthogonal polarizations, and extension into the higher frequency bands. Information theory and atmospheric effects define intrinsic limitations to some of these techniques. Accurate and rapid measurements, however, can

open doorways. For example, present minimum spacing in the geostationary orbit is four degrees for common frequency satellites. At present, the limitations of effective utilization of the orbit and spectrum depend solely upon the state-of-the-art of antennas, not upon the space transportation system. Sarkar [17] wrote: "The effective use of the geostationary orbit and the frequency bands have a direct bearing on these problems. The Radio Regulations and the studies made by the International Radio Consultative Committee (CCIR), although not yet conclusive, provide certain guidelines. The studies state that no simple comprehensive criteria have yet been developed to indicate whether or not satellite systems make efficient use of the geostationary orbit or the frequency spectrum." He goes on to say that antenna radiation pattern and cross-polarization performance are the two main parameters. At least two authors closely involved in the regulatory process point out that a reduction in sidelobe content of earth stations would increase the utilization of the geostationary orbit [17,18].

Present design techniques of large aperture antennas have gone through several generations of development over the past ten to fifteen years, beginning with early shaping techniques [19] and carrying through diffraction theory to more fully account for the effects of subreflector configuration and truncation [20]. We are now in a fourth generation of beam shaping, which has led to antennas approaching 80% aperture efficiency in the 4 and 6 GHz bands, including effects of spillover, depolarization, etc. The main purpose of these design techniques, however, has been to increase antenna efficiency, with the aim of optimizing G/T by obtaining maximum gain performance for a given physical size and decreasing far sidelobes to reduce the amount of high temperature earth seen by an antenna whose main lobe is looking at a cool sky. With the exception of the COMSAT "Torus" antenna (which is a section of a paraboloidal torus with multiple offset feeds) [21], however, little attention has been paid to suppression of sidelobe radiation lying specifically in the equatorial belt. With the burgeoning of small, inexpensive earth terminals, the sidelobe problem is likely to grow more, rather than less, severe. The difficulty of this problem is impressive. Sidelobe shaping requires extremely detailed attention to a very minor portion of the total energy radiated from the antenna. Care must be taken not to adversely affect the major radiation properties by causing boresight gain reduction, increased cross-polarization, defocussing, phase errors, squinting, and a variety of degradations. Although it is well known that a Gaussian illumination produces no sidelobes, this distribution makes such poor utilization of a given reflector diameter that it is not an acceptable solution to the sidelobe problem. In general, theoretical design techniques must be confirmed by measurements. Variations among individual units, even when standardized in production, suggest the need for testing after delivery

and installation at the customer's site. Several measurement techniques are in use [22] but accurate determination of sidelobe structure, including polarization characteristics, is presently limited to either near-field probing or measurements made on a true far-field range. Each of these has severe practical limitations. Near-field probing (i.e., measurements made on a plane, cylindrical, or spherical surface very close to the antenna and then mathematically transformed to obtain far-field characteristics) requires sophisticated instrumentation and advanced skills. Even with such capability, the measurement is slow and expensive for large antennas. For example, measurements on a 12-meter dish at 6 GHz would require some ten hours of actual measurement time (at 25 milliseconds per measured point) and five hours of processing time on a CDC 6600 computer [23]. Outdoor ranges, which attempt direct far-field measurements, involve expensive towers and considerable real estate. In order to be at least several Rayleigh distances away from the antenna (in the above example, a Rayleigh distance is 1.5 Km), examination of the sidelobes would require tall towers to eliminate multipath reflections. Other techniques, such as the "compact range" [22] are useful for boresight and main lobe examination but introduce sufficient aberration that sidelobe structure and cross-polarization errors become unacceptably large.

The advantages of earth station measurement by means of OSP immediately become apparent. Since it is a true far-field measurement, no extensive computer processing or specialized expertise is required. Such measurements can be done from either the manufacturer's plant or the user's earth station site, and include all effects introduced by the operating surroundings. With a drifting orbit of OSP, the antenna need not be taken offline for the measurement. One merely lets OSP move across the equatorial belt of the antenna, making measurements at programmed intervals over the period of a 12-hour half-oscillation of its synchronous, slightly elliptical, equatorial orbit. With such a readily available, inexpensive, accurate measurement technique yielding detailed sidelobe amplitude and polarization structure, several major benefits can be realized. Antenna design innovations and modifications can easily be tested and evaluated. This would advance the capability of equatorial sidelobe suppression such that more dense packing of geostationary satellites could be accomplished. The need for this is indicated by the density of present and planned satellites, as shown in figure 7. Specifically, in the fifty degrees of longitude encompassing the United States, eleven satellites are now deployed using the 6/4 GHz band (2 SATCOM's, 3 COMSTAR's, 3 ANIK's, 2 WESTAR's, and an ATS). One immediate benefit of being able to develop and regulate earth stations with improved sidelobe characteristics would be an increased orbit capacity of perhaps 20% to 50%. As a more far-reaching benefit, the development and production

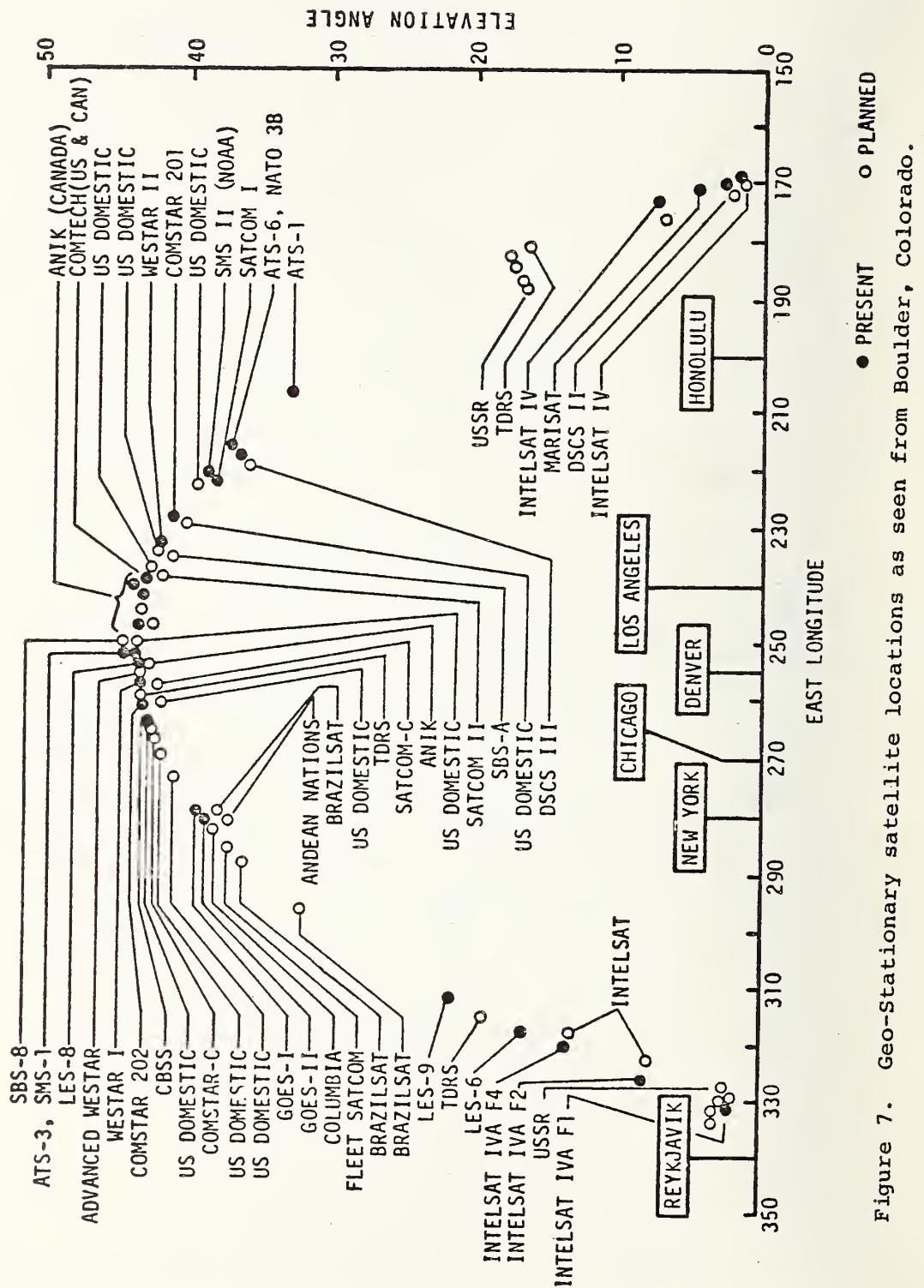


Figure 7. Geo-Stationary satellite locations as seen from Boulder, Colorado.

advantages provided to American industry would help maintain its present lead in the world equipment market. One of the United States' strongest principal exports is this production obtained from our electronics and communications high technology. This market is being penetrated by other nations [24], and the retention of the United States' advantage can be realized, by intensive efforts needed to keep us on the leading edge of technology development. The measurement capability of OSP will provide leverage when hammering out agreements in such international areas as the World Administrative Radio Conferences, and will strengthen our position of world technology leadership.

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APPENDIX I

THE NBS "SIX-PORT" POWER MEASURING SYSTEM

The "Six-Port" is a new concept in measuring microwave circuit parameters such as power flow, impedance, reflection coefficient, and scattering parameters in general. In the applications in OSP, we are expecting to use it for measuring net power flow (of the power transmitted from OSP) and incident power flow (of received power) with speed, accuracy, and high reliability.

In the accompanying illustrations, a simplified logical development of the six-port is shown.

In figure 8a, we have the problem statement. Power flows from the source on the left to the mismatched load on the right. The incident power, P_I , is that flowing down the line, but the net power delivered to the load is P_{NET} , which is the incident power reduced by the power reflected from the generally imperfect matched load. In OSP, when we are looking at power received by OSP, we wish to know the total received power irrespective of a mismatched down-converter; when we are monitoring a test signal transmitted by OSP, we wish to know only P_{NET} , the power delivered to the antenna.

An obvious method of measuring the power is to insert a calibrated directional coupler in the transmission line, as shown in figure 8b. The limitations of such a measurement are major: It measures P_I , and not P_{NET} and it has noncalibratable errors indicated by $\epsilon_1 \Gamma$ caused by mismatches at the load and source.

A refinement upon the preceding arrangement is to place two directional couplers back-to-back, as in figure 8c. This constitutes a "four-port" and permits direct measurement of the incident and reflected power, and therefore of P_{NET} . However, it still suffers from the introduction of noncalibratable errors indicated by the terms involving ϵ_2 and ϵ_3 because of load mismatch magnitude and angle.

A simple six-port is shown schematically in figure 9, and is completely calibratable for imperfect components in terms of the coefficients of each P_i and may be used to measure both P_I and P_{NET} . Figure 10 shows a realization of the six-port using power dividers, quadrature hybrids, and simple diode detectors, all of which can be built into a single microwave integrated circuit. It has the following additional advantages in this application:

1. High redundancy. Failure of any one of diodes P_5 through P_8 causes no reduction in performance. Failure of any two causes slight reduction in accuracy of phase measurement and essentially none in amplitude measurement. Failure of any three causes loss of phase measurement capability and some degradation in amplitude measurement. Failure of all four still permits a reduced accuracy measurement of amplitude which is the equivalent of figure 8b. (Note that P_3 is

necessary in all the above cases, and that a system for our purpose should also provide specific redundancy in this part of the six-port).

2. Phase measurements are obtainable without the need for phase-sensitive detectors.
3. Measurement speed is commensurate with the time required for moderate accuracy (12-bit) digitizing of the diode outputs, that is to say, the order of one to ten milliseconds.

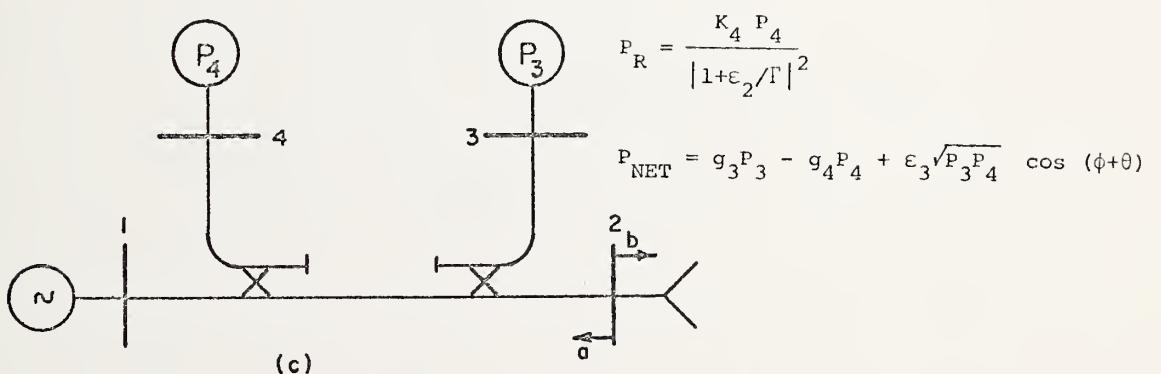
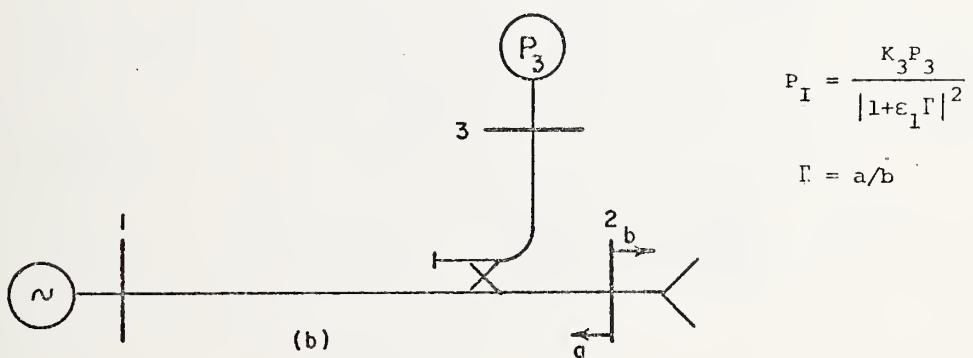
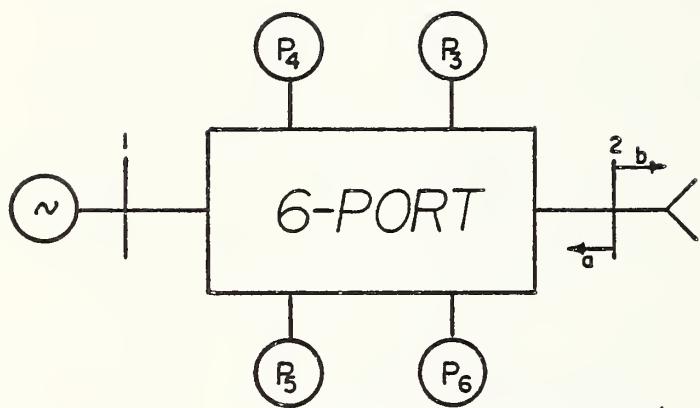


Figure 8. Six-Port progenitors.



$$P_I = \sum_i \beta_i P_i$$

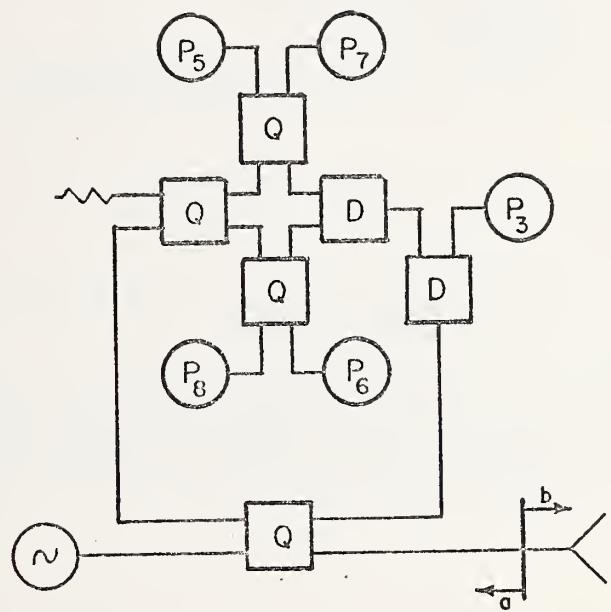
$$P_R = \sum_i \alpha_i P_i$$

$$P_{NET} = \sum_i q_i P_i$$

$$\Gamma = \frac{\sum_i z_i P_i}{\sum_i \beta_i P_i}$$

$$i = 3 \dots 6$$

Figure 9. 6-Port concept.



D = Power Divider

Q = Quadrature Hybrid

P = Diode Detector

Figure 10. A typical six-port, with redundancy.

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET		1. PUBLICATION OR REPORT NO. NBSIR 78-886	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE Feasibility Study of Orbiting Standards Platform		5. Publication Date June 1978		
7. AUTHOR(S) A.J. Estin and R.C. Baird		6. Performing Organization Code 723.05		
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234		10. Project/Task/Work Unit No. 7237276		
12. Sponsoring Organization Name and Complete Address (Street, City, State, ZIP)		13. Type of Report & Period Covered		
15. SUPPLEMENTARY NOTES		14. Sponsoring Agency Code		
16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.) This report consists of four components of a feasibility study for a satellite-based measurement system for determining important operational parameters of satellite communications systems and its major sub-systems. We have addressed the questions of required accuracy, methods of attaining and maintaining measurement accuracy and traceability, system tradeoffs, and economic impacts and benefits.				
17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons) Antenna gain; antenna measurements; antenna pattern; antenna sidelobes; G/T; EIRP; metrology for satellite communications.				
18. AVAILABILITY <input type="checkbox"/> For Official Distribution. Do Not Release to NTIS <input type="checkbox"/> Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13 <input checked="" type="checkbox"/> Order From National Technical Information Service (NTIS) Springfield, Virginia 22151		19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 47	
		20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price \$4.50	

